

Water Vapor in Carbon-rich AGB Stars from the Vaporization of Icy Orbiting Bodies

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ABSTRACT

We argue that the presence of water vapor in the circumstellar outflow of a carbon-rich AGB star is potentially a distinctive signature of extra-solar cometary systems. Detailed models show that at suitable distances from the star, water ice can survive well into the carbon-rich AGB phase; water vapor abundances as large as 10^{-6} could result from the vaporization of a collection of orbiting icy bodies with a total mass comparable to what might have been originally present in the solar system's Kuiper Belt. In particular, the recently-reported detection by the Submillimeter Wave Astronomy Satellite of water vapor in the circumstellar outflow of IRC+10216 can be explained if ~ 10 Earth masses of ice is present at a distance ~ 300 AU from that carbon-rich star. Future observations with the Herschel Space Observatory (HSO, formerly known as FIRST) will facilitate sensitive multi-transition observations of water, yielding line ratios that can establish the radial distribution of water vapor in IRC+10216. The greater sensitivity of HSO will also allow searches for water vapor to be carried out in a much larger sample of carbon-rich AGB stars.

Subject headings: Kuiper Belt – planetary systems – comets: general – stars: AGB and post-AGB – stars: individual (IRC+10216) – submillimeter

1. Introduction

One of the most exciting developments in astronomy during the past decade has been the unequivocal detection of extra-solar system planets of size as small as a few Jupiter masses (e.g. Mayor & Queloz 1995, Marcy & Butler 1996). This development suggests the possibility that planetary systems around other stars harbor yet smaller bodies, including

Earth-sized planets, asteroids and comets. The presence of comets, in particular, has been suggested by the β Pictoris phenomenon, in which time-variable line absorption is observed in a stellar spectrum at substantial Doppler shifts relative to the central star (Ferlet, Vidal-Madjar, & Hobbs 1987), suggesting comets evaporating as they speed near the central star. The discovery of extra-solar planetary systems also raises the question of how such systems change as the stars that they surround evolve.

Stern, Shull & Brandt (1990; hereafter SSB90) have pointed out when a star evolves off the main sequence, the resultant increase in its luminosity must lead to the vaporization of any icy bodies orbiting within several hundred AU, an effect that could result in the release of significant amounts of water vapor if the star were surrounded by a Kuiper Belt or Oort cloud. SSB90 considered the vaporization of icy bodies of various radii at various distances from a post-main-sequence star of constant assumed luminosity $6000 L_\odot$, and computed the resultant rate at which water vapor is deposited in the circumstellar environment. They suggested that this process could be responsible for the large water vapor and OH abundances typically observed in the circumstellar envelopes of oxygen-rich stars.

Although large water vapor abundances are in any case expected around oxygen-rich stars, and although the water outflow rates around many such sources greatly exceed what can plausibly be explained by the SSB90 model, recent measurements of modest water vapor abundances in two *carbon-rich* circumstellar outflows (Herpin & Cernicharo 2000, Melnick et al. 2001) motivate renewed attention to the mechanism proposed by SSB90. In particular, Melnick et al. have used the *Submillimeter Wave Astronomy Satellite* (SWAS) to detect water vapor emission from the classic carbon star IRC+10216. Carbon stars, which are late-type AGB stars where the carbon-to-oxygen ratio is greater than 1, are expected to harbor almost no water vapor in their circumstellar environments; the equilibrium chemistry of oxygen is dominated by CO and there is ordinarily very little oxygen left to

form any other molecules. The average water abundance predicted by standard chemical models for IRC+10216 (Millar et al. 2000) is less than 10^{-12} (Millar & Herbst 2001) and thus the presence of detectable water vapor in IRC+10216 may be a distinctive signature of the vaporization of orbiting icy bodies.

The existence of this signature rests critically upon the survival of such bodies. In particular, it is not possible to determine from the study of SSB90 whether *any* icy bodies will survive the ~ 1 Gyr of post-main-sequence evolution that precedes the carbon-rich phase (at least at radii where such bodies are plausibly present in the first place and where they would be subject to vaporization by a carbon-rich AGB star). To address this question we have extended the work of SSB90 by considering (1) the exact luminosity variations expected in a post-main-sequence star; (2) the size distribution and total mass of icy bodies expected if extra-solar cometary systems are similar to our own Kuiper Belt (the properties of which have been greatly elucidated [e.g. Jewitt & Luu 2000] since the work of SSB90); and (3) the specific application to carbon-rich stars, where the vaporization of icy bodies has the most distinctive observational signature. Our paper is organized as follows: in §2, we detail our theoretical model of the vaporization of a Kuiper Belt analog around a post-main-sequence star; in §3 we present the results of our calculations; the results are discussed in §4.

2. Calculations

For our standard model, we considered a star of mass $M_* = 1.5M_\odot$ and followed its luminosity evolution from the main sequence to the late AGB stage using evolutionary tracks kindly provided by Allen Sweigart. The luminosity, L , during the last ~ 2 Myr of the AGB track (the thermal pulsation or “TP-AGB” phase) is shown in Figure 1; the zero of time corresponds to the first thermal pulse on the AGB. The stellar

evolution model assumes a mass-loss rate, \dot{M}_* , given by the expression of Reimers (1975), $(\dot{M}_*/M_\odot \text{yr}^{-1}) = 4 \times 10^{-13} \eta_R (L/L_\odot) (R_*/R_\odot) (M_*/M_\odot)^{-1}$, where R_* is the stellar radius, and with the “Reimers parameter” η_R equal to 0.4. With this prescription for the mass-loss rate, the stellar mass has decreased to $1.4 M_\odot$ by the start of the AGB phase and to $0.92 M_\odot$ by the end of the AGB phase.

Using this model for the luminosity evolution of a $1.5 M_\odot$ star, we have calculated how a population of orbiting icy bodies would evolve. The mass loss rate per unit surface area, $\dot{m}(T)$, is described by the equation $\dot{m}(T) = P_s(T) (\mu/2\pi kT)^{1/2}$, where μ is the molecular mass of water, k is the Boltzmann constant and $P_s(T)$ is the vapor pressure of water ice at temperature T . This equation, which neglects gravitational effects, applies to bodies of radius $\lesssim 1000$ km for which the escape velocity is smaller than the typical outflow velocity of the vaporizing molecules ($\sim 1 \text{ km s}^{-1}$). Furthermore, it applies strictly to bodies composed of pure water ice rather than to bodies composed of a mixture of ice and refractory material. In large icy bodies (the size of Pluto and Charon), it is very plausible that differentiation will lead to a structure in which relatively pure ice surrounds a rocky core (McKinnon, Simonelli & Schubert 1997). In smaller bodies, however, the dust and ice will be well mixed and the effects of the refractory material on the vaporization rate is less clear – and may depend critically upon the size distribution of the dust (Prialnik 1992; Orosei et al. 1995). The average surface temperature in equilibrium, T , reached by an icy body at distance R from a star of luminosity L is given by $\epsilon\sigma T^4 = [(1 - A)L/(16\pi R^2) - H\dot{m}(T)]$, where A is the albedo, $H = 2.45 \times 10^{10} \text{ erg g}^{-1}$ is the specific heat of vaporization (Prialnik 1992), ϵ is the emissivity and σ is the Stefan-Boltzmann constant. Following SSB90, we adopt an albedo $A = 0.04$, an emissivity $\epsilon = 1$, and a vapor pressure $P_s(T) = 10^{9.183837 - 2403.4/T} \text{ torr}$ (Lebofsky 1975).

The mass-loss caused by vaporization reduces the radius of each orbiting icy body.

For a spherical body of uniform density ρ , the change in radius after time t is given by $\Delta r(t) = \int_0^t (\dot{m}(t')/\rho) dt'$. After time t , all objects of initial radius smaller than Δr have been completely vaporized. In computing the total mass loss rate from a population of orbiting icy bodies, we assume an initial size distribution of the form $dn/dr \propto r^{-q}$, where dn is the number of objects of radius r to $r+dr$. Recent observations (Jewitt & Luu 2000) of our own Kuiper Belt suggest $q \sim 4$ for radii r between $r_{\min} \sim 1$ km and $r_{\max} \sim 1200$ km (the size of Pluto); in other words, the size distribution has equal amounts of ice mass per logarithmic radius interval and the available reservoir of ice is dominated neither by small nor by large bodies. Although well-motivated by observations of the past decade, our assumption that the Kuiper belt contains objects with a range of sizes is not a critical one, and calculations with a single assumed object size yield qualitatively similar results.

3. Results

Our calculation shows that at the astrocentric radii of the classical Kuiper Belt, $R = 30 - 50$ AU (Jewitt & Luu 2000), even large icy bodies are entirely vaporized prior to the TP-AGB phase¹. Thus by the time the dredge-up of carbon has made the photospheric C/O ratio greater than 1, the release of water vapor can only take place if icy bodies are present at larger radii. Figure 2 shows the “complete vaporization radius”, R_{vap} , within which every icy body has been destroyed, as a function of time after the start of the TP-AGB phase. The solid curve shows the results for a size distribution extending to $r_{\max} = 1200$ km, the dotted curve for the case $r_{\max} = 120$ km, and the dashed curve for the

¹Note, however, that any icy bodies *originally* at the radius of the classical Kuiper Belt may have experienced significant outwards migration during the post-main-sequence evolution as a result of stellar mass-loss.

case $r_{\max} = 12$ km. Clearly, the complete vaporization radius is a slowly increasing function of r_{\max} , because larger bodies have a smaller surface-area-to-mass ratio and thus a longer lifetime.

Figure 3 shows the evolution of the water outflow rate and abundance for a collection of bodies located in circular orbits at fixed distance 200 AU from the central star. The mass-loss rate per unit initial ice mass, $\dot{M}(\text{H}_2\text{O})/M_0(\text{ice})$, is shown in Figure 3a for the case $r_{\max} = 1200$ km. The quantity $M_0(\text{ice})$ refers to the total mass of water ice present in the collection of orbiting bodies prior to the onset of evaporation. The same results appear in Figure 3b, but are now expressed as a water abundance, $x(\text{H}_2\text{O}) \equiv n(\text{H}_2\text{O})/n(\text{H}_2)$. Given a water mass outflow rate of $\dot{M}(\text{H}_2\text{O})$, the water abundance in the outflowing gas is $\frac{1}{9} \times \dot{M}(\text{H}_2\text{O}) / \frac{3}{4} \times \dot{M}_*$ relative to H_2 , the factor of $\frac{3}{4}$ being the mass fraction of hydrogen and the factor of $\frac{1}{9}$ being the ratio of the H_2 molecular mass to that of H_2O . Because the H_2 mass-loss rate is proportional to the Reimers parameter, η_R , the quantity plotted in Figure 3b is $x(\text{H}_2\text{O})\eta_R/M_0(\text{ice})$. We note that our use of the Reimers parameter η_R in Figure 3b is merely a useful way of parameterizing the mass-loss rate and that the results presented here apply *regardless* of whether “Reimers Law” is correct – i.e. regardless of whether η_R is a constant. Indeed, there is a developing consensus (e.g. Blöcker 1995, Willson 2000) that η_R is an increasing function of luminosity and that mass-loss occurs preferentially near the tip of the AGB. The current value of η_R for the high mass-loss star IRC+10216 is ~ 10 .

In Figures 4a and 4b, the water outflow rate and abundance are now shown *as a function of astrocentric distance, R* , at the three example evolutionary stages marked by open symbols on Figures 1 and 3. As in Figure 3, these results apply to a collection of icy bodies all located at a single distance, R , from the star. At any given time, the water outflow rate per unit initial ice mass shows a peak at some particular distance. At small distances from the star, the outflow rate and abundance increase as the assumed distance

gets larger because the amount of icy material remaining is an increasing function of R . (This increase is a gradual one because we assume the presence of a range of sizes for the orbiting icy bodies.) At large astrocentric distances, the outflow rate and abundances drop with increasing R because of the diminishing stellar flux. The radius at which $\dot{M}(\text{H}_2\text{O})/M_0(\text{ice})$ peaks moves outwards as the star evolves because of the steady increase in stellar luminosity on the AGB. Figure 4a implies that for icy bodies at the right distance from the star, water outflow rates as large as $\sim 10^{-5}M_0(\text{ice}) \text{ yr}^{-1}$ can plausibly be attained during the TP-AGB phase.

4. Discussion

The results presented above can now be discussed in the context of recent SWAS observations of the carbon-rich AGB star IRC+10216. The extraordinary stability of the SWAS receivers has allowed radiometric performance to be achieved in observations of duration as long as 200 hours (Melnick et al. 2000). Long duration observations have thereby achieved sensitivities considerably better than had been envisaged prior to the launch of SWAS. Such observations have led to the unexpected detection of the $1_{10} - 1_{01}$ 557 GHz transition of water vapor in emission toward IRC+10216 (Melnick et al. 2001; hereafter M01). The measured line strength implies a water abundance in the outflowing circumstellar envelope in the range $4 - 24 \times 10^{-7}$ (M01) corresponding to a water mass-loss rate of $2 - 4 \times 10^{-10}M_\odot \text{ yr}^{-1} = 0.6 - 1.4 \times 10^{-4}M_\oplus \text{ yr}^{-1}$. These exact values depend upon the H_2 mass-loss rate and the distance to IRC+10216, both of which are somewhat uncertain.

The exact initial mass of IRC+10216 is poorly-known but is believed to be between 1.5 and $4 M_\odot$ (Forestini, Guelin & Cernicharo 1997, Kahane et al. 2000). We have carried out calculations analogous to those presented in §3 with a stellar mass of $4 M_\odot$ in place of the

standard case $M_* = 1.5 M_\odot$; the results are qualitatively similar to those for the standard case, implying that our results are neither critically dependent upon the mass of the star nor upon the exact (and somewhat uncertain) details of the luminosity evolution model.

The results shown in Figure 4a and discussed in §3 above imply that the vaporization of icy bodies can explain the observed abundances of water vapor in the IRC+10216 outflow, given a total initial ice mass, $M_0(\text{ice})$, that can be as little as $10 M_\oplus$ if the icy bodies are located at a suitable radius. This value increases to $\sim 50 M_\oplus$ in a distributed model in which the icy bodies are assumed to be spread over a broad range of radii (40 – 400 AU) with the surface density of icy bodies proportional to R^{-2} . The exact value of $M_0(\text{ice})$ required depends upon several uncertain parameters, including the actual water abundance, the range of astrocentric radii at which icy bodies are present, the maximum object radius, and the evolutionary stage² of the star.

Although the properties of any Kuiper Belt analog around IRC+10216 might be quite different from those of our own Kuiper Belt, it is of interest to compare the required value of $M_0(\text{ice})$ with the mass inferred for the one system of which we have direct knowledge. Dynamical considerations place a limit of $\sim 1 M_\oplus$ upon the mass located at heliocentric radii in the range 30 – 50 AU (i.e. in the "classical Kuiper belt"), while recent detections of large Kuiper Belt Objects (KBOs) suggest a total mass $\sim 0.1 M_\oplus$ (Jewitt 1999), of which $\sim 50\%$ is likely water ice. Thus the observed amount of water ice currently present in the nearby classical Kuiper belt is far below what would be needed to account for the water abundance observed in IRC+10216. However, models for the formation of large KBOs such

²From the fact that IRC+10216 possesses one of the highest mass-loss rates of any known carbon star – a mass-loss rate some two orders of magnitude above the median value for carbon AGB stars – it seems likely that this source is in a stage of enhanced luminosity close to the tip of the AGB.

as Pluto (Kenyon & Luu 1998), suggest that the Kuiper Belt mass must *originally* have been at least $10 M_{\oplus}$ during the early history of the solar system; thus the vast majority of the material has likely been ejected to larger heliocentric distances in the Kuiper belt or Oort cloud where it cannot be detected in current surveys.

In addition to water vapor, the vaporization of comet-like icy bodies could release a distinctive mixture of other oxygen-bearing molecules that are not expected in carbon-rich environments but which are typically observed in comets. These include carbon dioxide and methanol. We are not aware of any detections of these molecules³ toward IRC+10216 nor of any upper limits that provide useful constraints upon their abundances.

The discussion presented above suggests that the vaporization of orbiting icy bodies is a plausible explanation for the water vapor detected in the circumstellar environment of IRC+10216. In addition, the vaporization scenario makes a specific prediction for the spatial distribution of the circumstellar water vapor. As the results in Figure 2 show, the vaporization of icy bodies injects water vapor into the outflow only at radii greater than ~ 75 AU. As noted by M01, the strength of the low-lying submillimeter transition observed by SWAS relative to higher-excitation far-infrared transitions will be higher in the vaporization scenario than would be the case were the water vapor abundance uniform throughout the envelope. While upper limits on far-infrared water line luminosities obtained by the *Infrared Space Observatory* (Cernicharo et al. 1996) provide marginal evidence against a uniform water abundance (M01), definitive observations of the water line ratios will have to await the greater sensitivity of the *Herschel Space Observatory* (HSO, formerly known as FIRST). The expected sensitivity of HSO – probably three orders of magnitude

³Latter & Charnley (1996) reported the detection of millimeter line emission at the frequencies of several methanol transitions, but subsequently favored C₄H and C₄H₂ as the species responsible for the emission originally attributed to methanol.

better than SWAS for observations at 557 GHz – will also allow searches for water vapor to be carried out in a much larger sample of carbon-rich AGB stars.

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Figure Captions

Fig. 1 – Evolutionary tracks for a $1.5 M_{\odot}$ star (kindly provided by Allen Sweigart). The luminosity, L , during the last ~ 2 Myr of the AGB track (the thermal pulsation or “TP-AGB” phase) is shown in Figure 1; the zero of time corresponds to the first thermal pulse on the AGB. Open symbols mark the three example evolutionary stages plotted in Figure 4.

Fig. 2 – Vaporization radius, R_{vap} , within which every icy body has been destroyed, as a function of time after the start of the TP-AGB phase. The solid curve shows the results for a size distribution extending to $r_{\text{max}} = 1200$ km, the dotted curve for the case $r_{\text{max}} = 120$ km, and the dashed curve for the case $r_{\text{max}} = 12$ km

Fig 3. – Evolution of the water outflow rate and abundance for a collection of bodies located in circular orbits at fixed distance 200 AU from the central star. The mass-loss rate per unit initial ice mass, $\dot{M}(\text{H}_2\text{O})/M_0(\text{ice})$, is shown in Figure 3a for the case $r_{\text{max}} = 1200$ km. The quantity $M_0(\text{ice})$ refers to the total mass of water ice initially present in the collection of orbiting bodies. The same results appear in Figure 3b, but are now expressed as a water abundance, $x(\text{H}_2\text{O}) \equiv n(\text{H}_2\text{O})/n(\text{H}_2)$. Open symbols mark the three example evolutionary stages plotted in Figure 4.

Fig 4. – Water outflow rate and abundance *as a function of astrocentric distance, R* , at the three example evolutionary stages marked by open symbols on Figures 1 and 3. The short-dashed line refers to the evolutionary stage marked by a triangle in Figures 1 and 3, the long-dashed line to that marked by a diamond, and the solid line to that marked by a star. As in Figure 3, the results in Figures 4a and 4b apply to a collection of icy bodies all located at a particular distance, R , from the star.







